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Mold Resistance and Water Absorption of Wood/HDPE and Bamboo/HDPE Composites

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Abstract: This study was conducted to clarify the mold resistance and water absorption of wood plastic composites (WPC). Wood/HDPE and bamboo/HDPE with different fiber content were used as test material. Mold fungi resistance (with or without biocide zinc borate (ZB)), scanning electron microscopy (SEM) analysis and water-absorption rate were investigated after 28 days incubation with *Aspergillus niger*, *Trihoderma viride*, *Penicillium funiculosum* and *Aureobasidium pullulans*. Mold resistance varied with fiber content and the incorporation of zinc borate. Composites contained higher fiber content was more susceptible to mold fungi. The addition of ZB remarkably improved the mold resistance of WPC. SEM analysis showed distinct evidence of mold growth and colonization on WPC specimen. Water absorption of WPC was jointly affected by wood or bamboo content, mold attack and temperature. Water absorption progressed quickly with higher fiber content and temperature and the mold growth also seemed to promote the water absorption of WPC.

Key words: Wood-plastic composites (WPC), mold fungi, mold resistance, water absorption rate

INTRODUCTION

Wood-plastics Composites (WPC) are thermoplastically processible composites that consist of natural fibers (such as wood, bamboo, bagasse, rice bran, etc.), plastics (such as polyethylene (PE), high density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC)) and additives. WPC has a broad market and a bright application prospect. Applications of WPC include building industry, furniture industry, automotive industry, measurement engineering and so on. Even though, WPC are generally considered to be more resistant to fungi due to the wood particle was encapsulated by plastic. However, with increasing fiber content and the commercial WPC formulations contain a nutrient source in the form of wood or other natural fibers, it can be assumed that WPC materials were susceptible to fungi.

Since Morris and Cooper observed the presence of fungal decay and discoloration on WPC deck boards in Florida (Morris and Cooper, 1998), fungi resistance of WPC has been studied by many researchers with the test fungi *Coniophora puteana*, *Coriolus versicolor*, *Gloeophyllum trabeum*, *Trametes versicolor*, *Postia placenta*, *Schizophyium commune*, *Pycnoporus sanguineus*, *Tyromyces palustris*, *Pycnoporus coccineus*, *Alternaria alternata* (Schirp and Wolcott, 2005; Wu *et al*., 2003; Pendleton *et al*., 2002; Clemons and Ibach, 2002; Schirp and Wolcott, 2006; Ashori *et al*., 2013; Wei *et al*., 2013; Hamzeh *et al*., 2012; Kartal *et al*., 2013; Naumann *et al*., 2012). Fungal durability of WPC were affected by plastic monomers type, wood species, wood content, particle size, chemically modified of wood fibers and additives such as lubricant, stabilizers, biocides, coupling agent (Wei *et al*., 2013; Chow *et al*., 2002; Verhey and Laks, 2002; McDonald *et al*., 2009; Morrell *et al*., 2009). High wood content in WPC generally resulted in more susceptible to mold and decay fungi. However, biocides can significantly improve the fungi resistance. On the other hand, some evidence revealed that WPC materials are also susceptible to mold fungi.

It was stated in a study that several manufacturing variables (wood content, lubricant type, fungicides and extruder temperature profile) have an effect on mold susceptibility of WPC. It was determined that an increase in wood content as well as surface roughness increased mold growth and that lubricants generally increased mold growth rates. However, fungicides will significantly

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reduce the mold growth on WPC and hemicelluloses extraction from the wood raw material results in improvement in mold resistance of the WPC (Hosseinaei *et al.*, 2012). H'ng *et al.* (2011) and Kartal *et al.* (2013) also reported the mold growth and coverage on WPC specimens after 4 week incubation.

Water absorption is an important factor influencing properties and durability of WPC materials (Gnatowski, 2005). The presence of water in WPC decreases mechanical properties and durability, including interfacial shear strength, ultimate elongation, maximum strength, tensile property, flexural strength and microbiological activity (Gnatowski, 2005; Chen *et al.*, 2009; Kim and Seo, 2006; Dhakal *et al.*, 2007; Espert *et al.*, 2004). It was determined that water absorption provided a favorable environment for fungi growth, directly or indirectly increased the susceptibility of WPC to fungal attack (Defoirdt *et al.*, 2010; Stark, 2005; Wang and Morrell, 2004). Water uptake leads to the degradation of the fibers and the fiber-matrix interface, caused the material to warping, swelling, etc (Espert *et al.*, 2004). Stiffness of WPC was affected more severely by moisture absorption than by fungal decay (Schirp and Wolcott, 2005).

However, litter information has been done about the effects of mold attack and growth on water absorption of WPC. Therefore, this study was carried out to investigate the mold durability of wood/HDPE and bamboo/HDPE composites contained different fiber content (40, 50, 60 and 70%) and WPC produced from 60% wood or bamboo loading and 1.5% Zinc Borate (ZB). Water absorption of WPC after 28 days exposure to mold fungi was performed to observe the effects of mold growth on water uptake of WPC specimens.

MATERIALS AND METHODS

Preparation of WPC composites: Ten WPC formulations No. 1-10 (Table 1) were used in this study. For each composite formulation, 60-mesh pine wood flour No. 1-5 or bamboo flour No. 6-10, with different content 40, 50, 60 and 70%, were used as the filler for HDPE thermoplastic matrix material. 1.5% (by weight) zinc borate (Zibo Wuwei Industrial Co., Ltd) was added in No. 5 and No.10. WPC samples were cut into 20 mm×40 mm×4.5 mm size after composites were compressed.

Mold resistance tests: Mold resistance tests were conducted in according to the American Society for Testing and Material (ASTM G21-09). Four mold fungi, *Aspergillus niger* (ATCC 16404), *Trihoderma viride* (As 3.2941), *Penicillium funiculosum* (GIM 3.103) and *Aureobasidium pullulans* (AS 3.387) were grown and maintained on potato dextrose ager (PDA) at 28°C and 80% RH. A mixed spore suspension of the four test fungi was prepared by washing the surface of individual 10-day-old petri plate cultures with 10 to 15 mL of sterile water. Washings were combined in a spray bottle and diluted to approximately 100 mL with sterile water to yield approximately 1×10^7spores mL^{-1}. WPC specimens were sprayed with mixed mold spore suspension and incubated at 28°C and 80% RH for 28 days. Following incubation, specimens were visually rated as Table 2.

Scanning electron microscopy (SEM) analysis: Scanning electron microscopy (SEM) analysis of WPC surface was investigated after mold test. SEM of WPC specimens were examined using a HITACHI S-3000N emission scanning electron microscope, operated at 25 kV. Sections of WPCs samples before and after mold tests were cut into approximately 5 mm and mounted with carbon tape on aluminum stubs and then sputter coated with gold to make them conductive prior to SEM observation.

Water absorption tests: Following determination of mold resistance, dried WPC specimens to a constant mass in a ventilated oven at a temperature of 100°C and weighed to the nearest 0.001 g (W_0). Placed WPC specimens in a container of distilled water at temperature of 25 and 60°C. After 1, 2, 4, 8, 16, 32, 48, 96, 192, 384 and 768 h water immersion, removed WPC specimen from water, wiped all surface water off with a dry cloth and weighed immediately (W_t). Water absorption (WA) was calculated using the following equation:

$$WA\ (\%) = \frac{W_t - W_0}{W_t} \times 100$$

Table 1: Formulation of wood plastic composites

WPC type	No.	WPC formulation (w/w %)
Wood/HDPE	1	wood/HDPE (40/60)
	2	wood/HDPE (50/50)
	3	wood/HDPE (60/40)
	4	wood/HDPE (70/30)
	5	wood/HDPE/ZB (60/40/1.5)
Bamboo/HDPE	6	bamboo/HDPE(40/60)
	7	bamboo/HDPE(50/50)
	8	bamboo/HDPE(60/40)
	9	bamboo/HDPE(70/30)
	10	bamboo/HDPE/ZB (60/40/1.5)

Table 2: Evaluation method for mold growth on WPC sample surface

Ratings	Observed growth on specimens
0	None
1	Traces of growth (<10%)
2	Light growth (10-30%)
3	Medium growth (30-60%)
4	Heavy growth (60% to complete coverage)

RESULTS AND DISCUSSION

Mold resistance: Mold resistance of wood/HDPE and bamboo/HDPE specimens were visually rated after exposed to mold fungi for 7 days, 14 days and 28 days, respectively. As shown in Table 3, mold growth and coverage increased with increasing fiber content both on wood and bamboo/HDPE. After 7, 14 and 28 days exposure, WPC samples contained 40% wood or bamboo flour found to be mold resistance than those specimens with higher fiber flour loading (50, 60 or 70%). Mold growth increased with an increasing wood content, consistent with studies of Laks *et al.* (2005) and H'ng *et al.* (2011). However, Kartal *et al.* (2013) found that no relation between mold resistance and wood or bamboo content, all WPC specimens were 100% coverage by the mold fungi after just a 4-week-incubation.

Bamboo/HDPE samples showed a higher susceptibility to mold growth than wood/HDPE composites with and without ZB. Ratings of wood/HDPE samples with 40% or 50% fiber content were 1 and 2 but bamboo/HDPE contained the same fiber content were rated 2 and 3, respectively. However, when the fiber content up to 60% or 70%, all WPC specimens, both wood/HDPE and bamboo/HDPE, were covered completely by mold fungi after 28 days incubation. It was reported that there was significant relationship between fungi resistance and wood species. Fabiyi *et al.* (2011) found that the fungi durability was affected by wood species, weight losses caused by *Gloeophyllum trabeum* on WPCs containing Douglas fir, ponderosa pine and hybrid poplar were 2-3 times higher than those WPCs containing either black locust or white oak.

The addition of ZB into WPC effectively prevented mold attack on WPC composites. Wood/HDPE (60/40) and bamboo/HDPE (60/40) with 1.5% ZB were highly resistance to mold than those WPC without ZB (Table 3). 1.5% concentration of ZB could completely prevented mold growth and coverage on wood/HDPE, no mold growth was found on specimens after 28 days incubation. However, the use of 1.5% ZB did not completely control surface mold on bamboo/HDPE, in order to prevented mold growth completely, higher concentration of ZB should be used.

The ues of ZB in preventing fungal decey and mold growth has been previously investigated. Pendleton *et al.* (2002) found the WPC formulations with ZB at 2% concentration can prevent any weight loss of extruded wood/HDPE composite. Verhey *et al.* (2001) reported 1.0% ZB loading effectively prevented fungal attack on wood fiber and thermoplastic composites. Klyosov (2007) stated that ZB in amounts of 0.5, 1 and 2% in WPCs practically stopped the microbial degradation in the AWPA laboratory soil block tests. However, the use of ZB did not completely control surface mold on the WPC decks exposed in outdoor filed tests. 1% ZB did not affect mold development on wood/PE, only 3 and 5% of ZB were effective. Kartal *et al.* (2013) also reported that 0.6% ZB have no inhibitory effect for any of the wood/PP or bamboo/PP specimens.

Table 3: Rating of WPC composites after exposure to mold fungi for 7, 14 and 28 days

WPC type	Fiber/HDPE (wt/wt %)	Concentration of ZB (wt/wt %)	Mold ratings 7 d	14 d	28 d
Wood/HDPE	40/60	0.0	0	1	1
	50/50	0.0	1	1	2
	60/40	0.0	1	2	4
	70/30	0.0	2	3	4
	60/40	1.5	0	0	0
Bamboo/HDPE	40/60	0.0	1	2	2
	50/50	0.0	1	2	3
	60/40	0.0	3	4	4
	70/30	0.0	4	4	4
	60/40	1.5	0	1	2

Scanning electron microscopy (SEM) analysis of WPC: SEM analysis showed distinct evidence of mold growth and colonization on WPC specimen (Fig. 1). After exposed to mold fungi for 28 days, mycelium concentrated in the interfacial gaps, both in wood/HDPE and bamboo/HDPE materials, between the wood and thermoplastic component near the specimen surface. However, there was no mold hyphae and spores be found in the samples that non-incubated with mold fungi.

Pendleton *et al.* (2002) reported that all WPC exit interfacial gap between the wood fine and the polymer matrix, the mycelium will appear to be concentrated in the gap and the mycelium will penetration into the materials.

Water absorption of wood/HDPE and bamboo/HDPE: Water absorption (WA) of wood/HDPE and bamboo/HDPE with 40, 50, 60 and 70% wood or bamboo filler after 28 days of mold incubation were measured and the samples non-incubated with mold fungi were used as control samples. WA of tested samples varied with the wood content, temperature and mold growth.

WA of moldy and control wood/HDPE and bamboo/HDPE composites with different wood content at 25°C were presented in Fig. 2 and 3. WA (both moldy and control samples) increased quickly with an increasing wood or bamboo content. For example, WA of moldy wood/HDPE with 40, 50, 60 and 70% wood filler after a 768 h water immersion were 2.59, 6.1, 11.71 and 16.34%, respectively. In contrast, MC of moldy bamboo /HDPE at 768 h were 4.62, 9.23, 11.53 and 11.97%, respectively, varied with the bamboo content 40, 50, 60 and 70%.

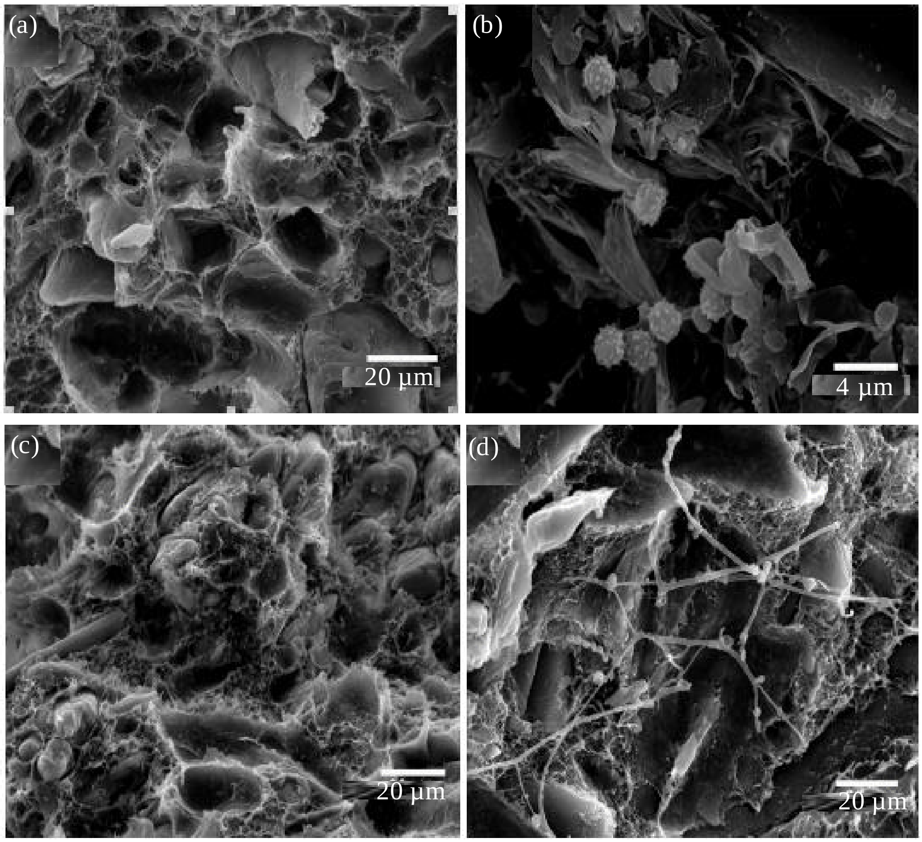

Fig. 1(a-d): SEM of wood/HDPE and bamboo/HDPE contained 60% fiber before and after exposure to mold fungi for 28 days. (a) Wood/HDPE before mold exposure, (b) Wood/HDPE after mold exposure, (c) Bamboo/HDPE after mold exposure and (d) Bamboo/HDPE before mold exposure

Schirp and Wolcott (2005) and Gnatowski (2005) stated that higher wood concentrations may promoted water absorption. Compatibility between wood particles (hydrophilic) and plastic (hydrophobic) can affect water absorption, with the increase of the amount of wood or bamboo particles in WPC composite, their polar character increases, resulting in higher water content (Schirp and Wolcott, 2005; Kartal *et al*., 2013). In addition, the amount of hydrophilic OH groups will be increased with the increasing of wood-filler content and that also resulted to increase of water uptake (Tajvidi and Ebrahimi, 2003).

Mold growth on surface of WPC seemed to promote the WA both for wood/HDPE and bamboo/HDPE. WA in moldy samples was higher than control samples which have the similar formulations. Figure 4 was the WA of wood/HDPE and bamboo/HDPE composites after 48 and 768 h of water-soaking at 25°C. As Fig. 4 showed, difference of WA between moldy and control wood/HDPE after 48 h immersion at 25°C, with the wood filler 40, 50, 60 and 70%, were 28.43, 49.55, 44.41 and 64.47% and difference at 768 h were 1.16, 23.11, 26.47 and 35.13%, respectively. There was also a significant difference between moldy and control bamboo/HDPE, difference at 48 h were 33.33, 48.21, 42.63 and 40.9%, at 768 h were 29.44, 15.52, 11.54 and 13.45%, separately, corresponding to the bamboo content 40, 50, 60 and 70%.

Hosseinaei *et al.* (2012) studied the effect of hemicellulose extraction on water absorption and mold susceptibility of WPC and they found WPC samples with the lowest mold susceptibility also had the lowest moisture absorption. Besides, additions of ZB, wood content ratio, wood particle size and increased surface area via surface grooves (channels) were affected the moisture infusion of WPC (Tascioglu *et al*., 2013).

Temperature also influenced the water absorption speed of WPC both for wood/HDPE and bamboo/HDPE.

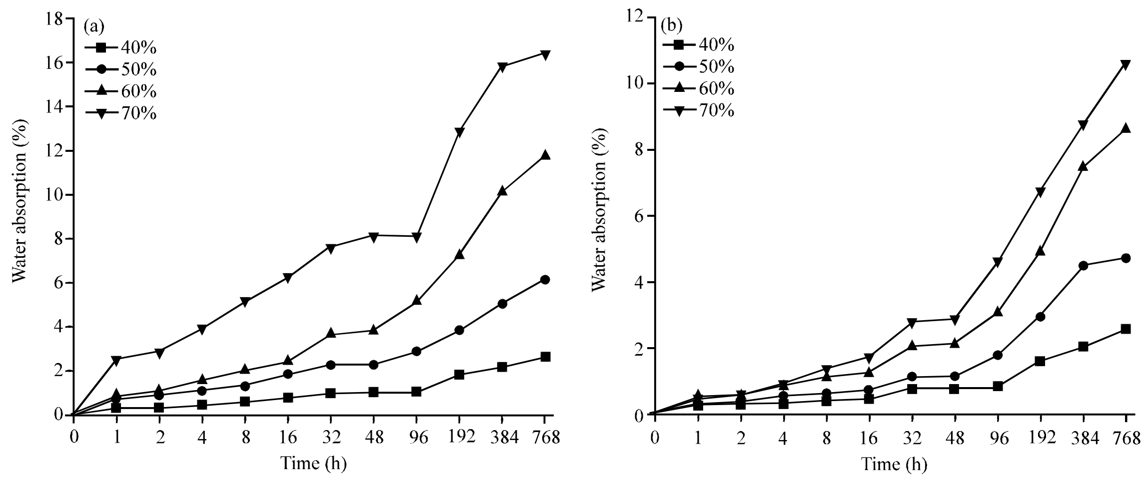

Fig. 2(a-b): Water absorption of (a) Moldy and (b) Control wood/HDPE samples at 25°C

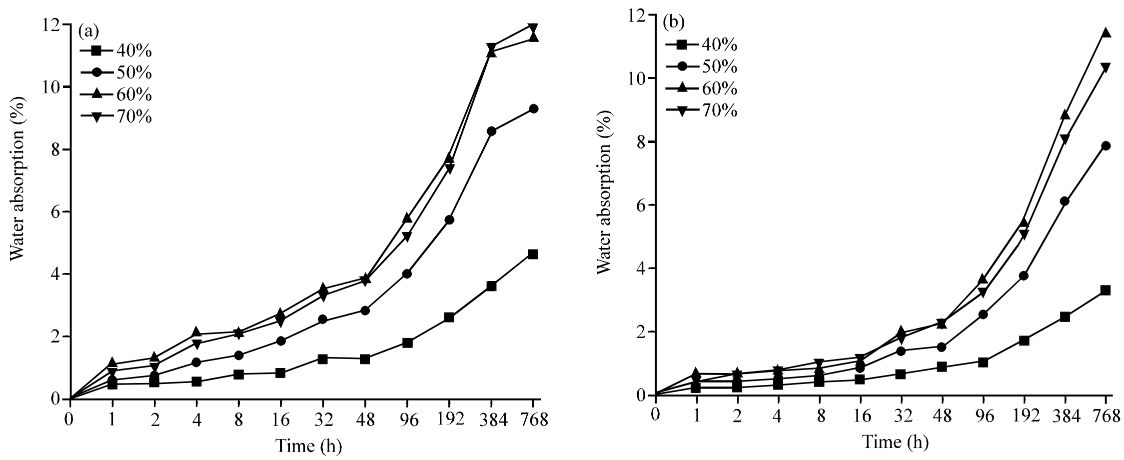

Fig. 3(a-b): Water absorption of (a) Moldy and (b) Control bamboo/HDPE samples at 25°C

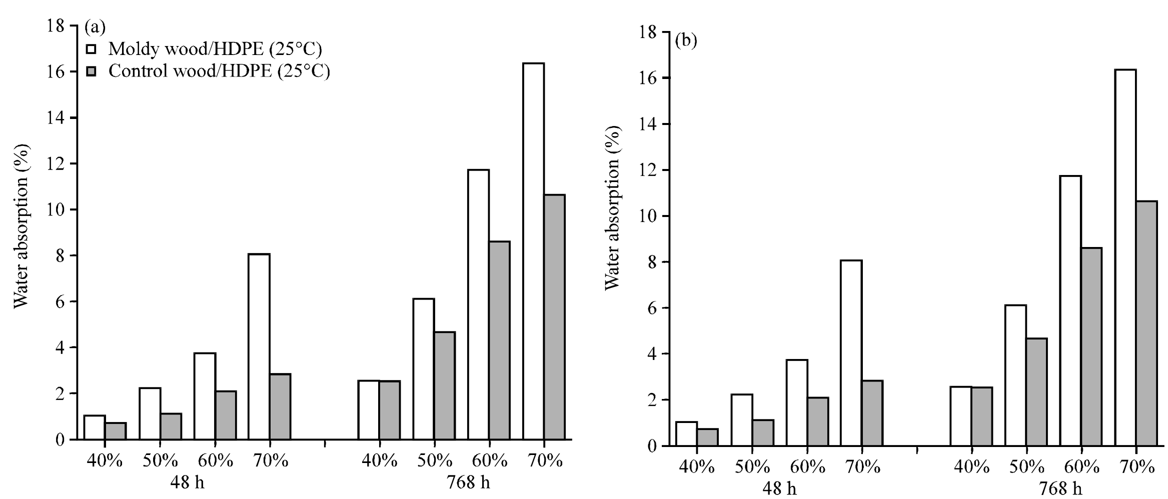

Fig. 4(a-b): Water absorption of (a) Wood/HDPE and (b) Bamboo/HDPE composites after 48 and 768 h of water-soaking at 25°C

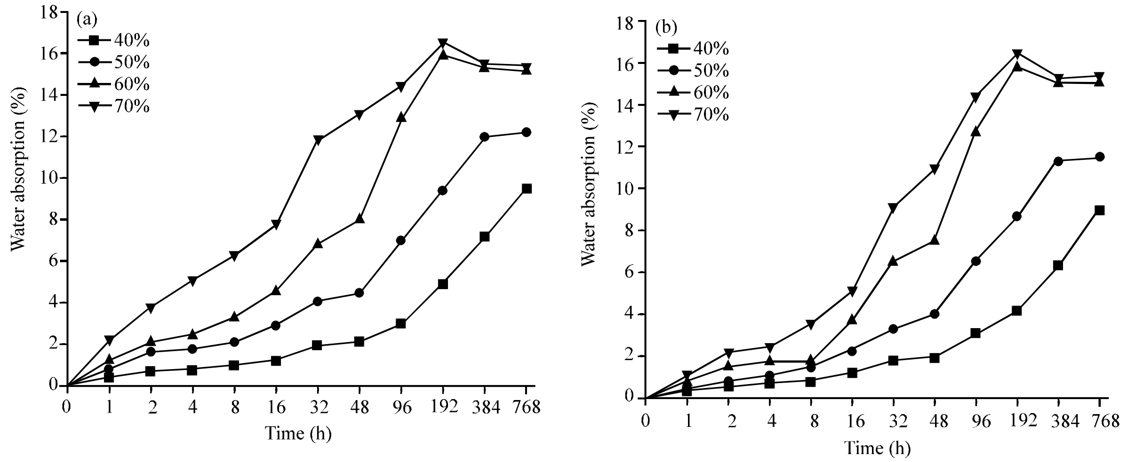

Fig. 5(a-b): Water absorption of (a) Moldy and (b) Control wood/HDPE composites at 60°C

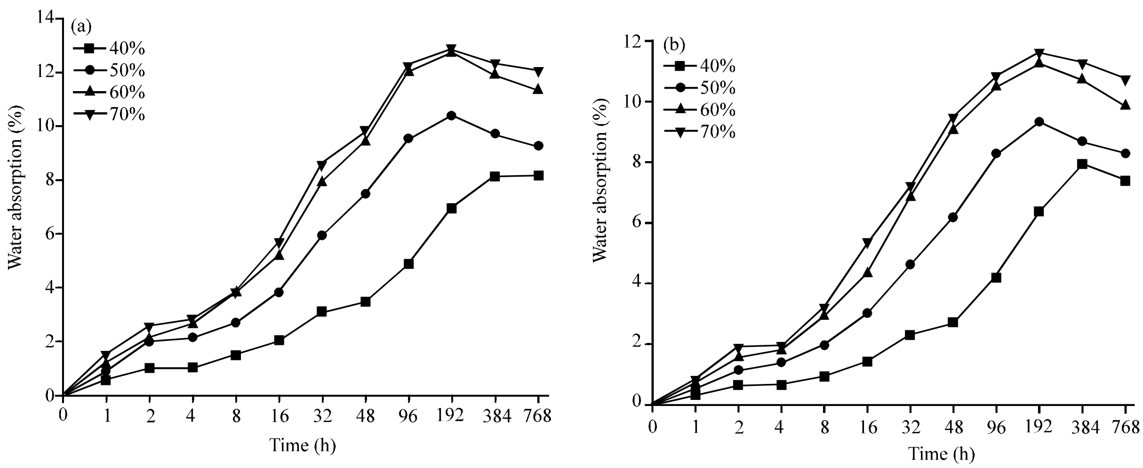

Fig. 6(a-b): Water absorption of (a) Moldy and (b) Control bamboo/HDPE composites at 60°C

Samples immersed in 60°C water showed significantly higher water uptake speed than those exposedin 25°C water. As Fig. 5 and 6 showed, WA of wood/HDPE and bamboo/HDPE at 60°C also increased with the wood or bamboo content and the WA of moldy samples were higher than control samples. Hoverer, comparing with WA at 25°C (Fig. 2 and 3), samples immersed in 60°C water showed significantly higher water uptake speed, indicated that temperature also influenced the water absorption of WPC. At 60°C temperature of water immersion, wood/HDPE and bamboo/HDPE specimen reached an equilibrium level only after 192 or 384 h water-soaking. But when immersed in water at 25°C, tested samples had not completely reached its WA equilibrium yet after 768 h water-immersion.

CONCLUSION

Mold growth on wood/HDPE and bamboo/HDPE caused by mold fungi was directly related to fiber content, fiber species and addition of ZB. WPC contained higher fiber content were more susceptible to mold fungi. Wood/HDPE showed higher mold resistance than bamboo/HDPE which contained the same quantity of the fiber. The addition of ZB provided more resistance against mold fungi and prevented mold growth in WPC.

Visual appearance and SEM analysis showed distinct evidence of mold growth and colonization on surface of wood/HDPE and bamboo/HDPE composites. After a period of 28 days exposed, all composites without ZB were colonized and covered by the mold fungi. Mycelium concentrated in the interfacial gaps between the wood and thermoplastic component was also observed by SEM.

Water absorption of WPC was affected by wood or bamboo content, mold attack and temperature. With the increase of wood or bamboo content, water absorption progressed very quickly. Mold growth on surface of WPC seemed to promote the water absorption. Water absorption in moldy samples was higher than control samples which have the similar formulations. Temperature also influenced the water absorption speed of WPC. Samples immersed in 60°C water showed significantly higher water uptake speed than those exposed in 25°C water.

REFERENCES

Ashori, A., H.M. Behzad and A. Tarmian, 2013. Effects of chemical preservative treatments on durability of wood flour/HDPE composites. Comp. B: Eng., 47: 308-313.

Chen, H.Y., M.H. Miao and X. Ding, 2009. Influence of moisture absorption on the interfacial strength of bamboo/vinyl ester composites. Compos. A: Applied Sci. Manuf., 40: 2013-2019.

Chow, P., F.S. Nakayama, J.A. Youngquist, J.H. Muehl and A.M. Krzysik, 2002. Durability of wood/plastic composites made from *Parthenium* species. Proceedings of the 33rd Annual Meeting of the International Research Group in Wood Preservation, May 14-17, 2002, Cardiff, Wales, UK., pp: 2-11.

Clemons, C.M. and R.E. Ibach, 2002. Laboratory tests on fungal resistance of wood filled polyethylene composites. Proceedings of the 60th Annual Technical Conference and Exhibition, Volume 48, May 5-9, 2002, San Francisco, CA., USA., pp: 2219-2222.

Defoirdt, N., S. Gardin, J. van der Bulcke and J. van Acker, 2010. Moisture dynamics of WPC and the impact on fungal testing. Int. Biodeter. Biodegr., 64: 65-72.

Dhakal, H.N., Z.Y. Zhang and M.O.W. Richardson, 2007. Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. Comp. Sci. Technol., 67: 1674-1683.

Espert, A., F. Vilaplana and S. Karlsson, 2004. Comparison of water absorption in natural cellulosic fibres from wood and one-year crops in polypropylene composites and its influence on their mechanical properties. Comp. A: Applied Sci. Manuf., 35: 1267-1276.

Fabiyi, J.S., A.G. McDonald, J.J. Morrell and C. Freitag, 2011. Effects of wood species on durability and chemical changes of fungal decayed wood plastic composites. Comp. A: Applied Sci. Manuf., 42: 501-510.

Gnatowski, M., 2005. Water absorption by wood plastic composites in exterior exposure. Proceedings of the 8th International Conference on Wood Fiber-Plastic Composites, May 23-25, 2005, Madison, Wisconsin, USA., pp: 1-18.

H'ng, P.S., A.N. Lee, C.M. Hang, S.H. Lee, A. Khalina and M.T. Paridah, 2011. Biological durability of injection moulded wood plastic composite boards. J. Applied Sci., 11: 384-388.

Hamzeh, Y., A. Ashori, E.H. Marvast, K. Rashedi and A.M. Olfat, 2012. A comparative study on the effects of *Coriolus versicolor* on properties of HDPE/wood flour/paper sludge composites. Comp. B: Eng., 43: 2409-2414.

Hosseinaei, O., S. Wang, A.D. Taylor and J.W. Kim, 2012. Effect of hemicellulose extraction on water absorption and mold susceptibility of wood-plastic composites. Int. Biodeter. Biodegr., 71: 29-35.

Kartal, S.N., S. Aysal, E. Terzi, N. Yilgor, T. Yoshimura and K. Tsunoda, 2013. Wood and Bamboo-PP composites: Fungal and termite resistance, water absorption and FT-IR analyses. BioResources, 8: 1222-1244.

Kim, H.J. and D.W. Seo, 2006. Effect of water absorption fatigue on mechanical properties of sisal textile-reinforced composites. Int. J. Fatigue, 28: 1307-1314.

Klyosov, A.A., 2007. Wood-Plastic Composites. John Wiley and Sons, New Jersey, pp: 442-443.

Laks, P.E., K. Vehring, S. Verhey and D.L. Richter, 2005. Effect of manufacturing variables on mold susceptibility of wood-plastic composites. Proceedings of the 8th International Conference on Wood Fiber-Plastic Composites, May 23-25, 2005, Madison, Wisconsin, USA., pp: 265-270.

McDonald, A.G., J.S. Fabiyi, J. Morrell and C. Freitag, 2009. Effect of wood species on the weathering and soil performance of wood plastic composites. Proceedings of the 10th International Conference on Wood and Biofiber Plastic Composites and Cellulose NanoComposites Symposium, May 11-13, 2009, Madison, Wisconsin, USA., pp: 84-89.

Morrell, J.J., N.M. Stark, D.E. Pendleton and A.G. McDonald, 2009. Durability of wood-plastic composites. Proceedings of the 10th International Conference on Wood and Biofiber Plastic Composites and Cellulose NanoComposites Symposium, May 11-13, 2009, Madison, Wisconsin, USA., pp: 71-75.

Morris, P.I. and P. Cooper, 1998. Recycled plastic/wood composite lumber attacked by fungi. For. Prod. J., 48: 86-88.

Naumann, A., I. Stephan and M. Noll, 2012. Material resistance of weathered wood-plastic composites against fungal decay. Int. Biodeter. Biodegr., 75: 28-35.

Pendleton, D.E., T.A. Hoffard, T. Adcock, B. Woodward and M.P. Wolcott, 2002. Durability of an extruded HDPE/wood composite. Forest Prod. J., 52: 21-27.

Schirp, A. and M.P. Wolcott, 2005. Influence of fungal decay and moisture absorption on mechanical properties of extruded Wood-plastic composites. Wood Fiber Sci., 37: 643-652.

Schirp, A. and M.P. Wolcott, 2006. Fungal degradation of wood-plastic composites and evaluation using dynamic mechanical analysis. J. Applied Polym. Sci., 99: 3138-3146.

Stark, N.M., 2005. Changes in wood flour/HDPE composites after accelerated weathering with and without water spray. Proceedings of the 2nd Wood Fibre Polymer Composites Symposium: Applications and Perspectives, March 24-25, 2005, Bordeaux, France, pp: 1-12.

Tajvidi, M. and G. Ebrahimi, 2003. Water uptake and mechanical characteristics of natural filler-polypropylene composites. J. Applied Polym. Sci., 88: 941-946.

Tascioglu, C., T. Yoshimura and K. Tsunoda, 2013. Biological performance of wood-plastic composites containing zinc borate: Laboratory and 3-year field test results. Comp. B: Eng., 51: 185-190.

Verhey, S., P. Laks and D. Richiter, 2001. Laboratory decay resistance of wood fiber/thermoplastic composites. Forest Prod. J., 51: 44-49.

Verhey, S.A. and P.E. Laks, 2002. Wood particle size affects the decay resistance of woodfiber/thermoplastic composites. Forest Prod. J., 52: 78-81.

Wang, W.H. and J.J. Morrell, 2004. Water sorption characteristics of two wood-plastic composites. Forest Prod. J., 54: 209-212.

Wei, L., A.G. McDonald, C. Freitag and J.J. Morrell, 2013. Effects of wood fiber esterification on properties, weatherability and biodurability of wood plastic composites. Polym. Degrad. Stabil., 98: 1348-1361.

Wu, Q., S. Lee and J. P. Jones, 2003. Decay and mold resistance of borate modified oriented strandboard. Proceedings of the 34th Annual Conference for the International Research Group on Wood Preservation, May 18-23, 2003, Brisbane, Australia, pp: 1-13.